Role of ocean biology-induced climate feedback in the modulation of El Niño-Southern Oscillation

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[1] El Niño-Southern Oscillation (ENSO) properties can be modulated by many factors; most previous studies have focused on physical aspects of the climate system in the tropical Pacific. Ocean biology-induced feedback (OBF) onto physics and bio-climate coupling have been the subject of much recent interest, revealing striking model dependence and even conflicting results. Current satellite data are able to resolve the space-time structure of oceanic signals both in biology and physics, providing an opportunity for quantifying their relationships. Here we use the biological signature from satellite ocean color data to estimate interannual variability of the attenuation depth of solar radiation (H_p), a field linking ocean biology and physics. We then apply a singular value decomposition (SVD) analysis to interannual H_p and sea surface temperature (SST) anomaly fields to derive an empirical H_p model which is incorporated in a hybrid coupled ocean-atmosphere model of the tropical Pacific to represent the OBF. It is shown that the OBF can have significant effects on ENSO behaviors, including its amplitude, oscillation periods and seasonal phase locking.

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1. Introduction

[2] El Niño-Southern Oscillation (ENSO) exhibits considerable variability as seen in a number of extensive and intensive studies, which have mostly emphasized the roles of physical processes [e.g., *Zhang and Busalacchi*, 2008; *Zhang et al.*, 2008]. Recent studies have demonstrated that changes in ocean biology can affect ENSO behaviors as well [e.g., *Timmermann and Jin*, 2002]. Indeed, biological conditions in the tropical Pacific Ocean are strongly regulated by physical changes associated with the ENSO [e.g., *Chavez et al.*, 1999]. The existence and variation of phytoplankton biomass, in turn, modulate the vertical penetration of solar radiation in the upper ocean, presenting a feedback from ocean biology to physics and climate [e.g., *Strutton and Chavez*, 2004; *Wang et al.*, 2005]. The effects of ocean biology can be simply represented by the penetration depth of solar radiation in the upper ocean (H_p), a field thus serving as a link between the climate system and the marine ecosystem [e.g., *Murtugudde et al.*, 2002; *Ballabrera-Poy et al.*, 2007]. In the tropical Pacific, interannual H_p anomalies are observed to be large during ENSO cycles and their importance in the mixed layer heat budget has been demonstrated in many previous studies [e.g., *Lewis et al.*, 1990; *Sweeney et al.*, 2005; *Manizza et al.*, 2005]. Therefore, the ocean biology-induced feedbacks need to be adequately taken into account in diagnostic and modeling studies. However, the effects on mean climate and its variability are strikingly model dependent and even conflicting [e.g., *Nakamoto et al.*, 2001; *Murtugudde et al.*, 2002], indicating a clear need for more detailed investigations.

[3] At present, there are great uncertainties in representing ocean biology-related effects and bio-climate interactions in coupled ocean-atmosphere models on basin or global scales [e.g., *Marzeion et al.*, 2005; *Wetzel et al.*, 2006; *Manizza et al.*, 2005; *Lengaigne et al.*, 2007; *Anderson et al.*, 2007]. In particular, current comprehensive ocean biogeochemistry models still have considerable difficulty of realistically simulating H_p anomalies during ENSO cycles. Alternatively, a statistical approach can be taken as the advance of space-based satellite observations has provided unprecedented basin-wide ocean color data [*McClain et al.*, 1998]. In particular, these data have been used to estimate the mean structure, seasonal and interannual variability of the H_p fields [e.g., *Murtugudde et al.*, 2002; *Ballabrera-Poy et al.*, 2007]. In this work, we explore the possibility of an empirical derivation of interannual H_p variability in the tropical Pacific, which is then incorporated in a coupled ocean-atmosphere model of intermediate complexity to represent the OBF and bio-climate interactions.

2. Data and Models

2.1. H_p Fields Derived From Satellite Ocean Color Data

[4] Current high quality ocean color data can resolve biology-related signals in the ocean [e.g., *McClain et al.*, 1998], providing an opportunity for describing interannual variability in ocean biology and its coupling with physics. Following *Murtugudde et al.* [2002] and *Ballabrera-Poy et al.* [2007], the monthly H_p fields are derived from remotely sensed chlorophyll from September 1997 to April 2007. Note that the focus here is on interactive representation of H_p in terms of physical changes, and not on the actual magnitudes of simulating penetrative radiation since the latter do not change the major conclusions of our study.

[5] In the tropical Pacific, large interannual anomalies are evident in the SST and H_p fields (Figure 1), with their

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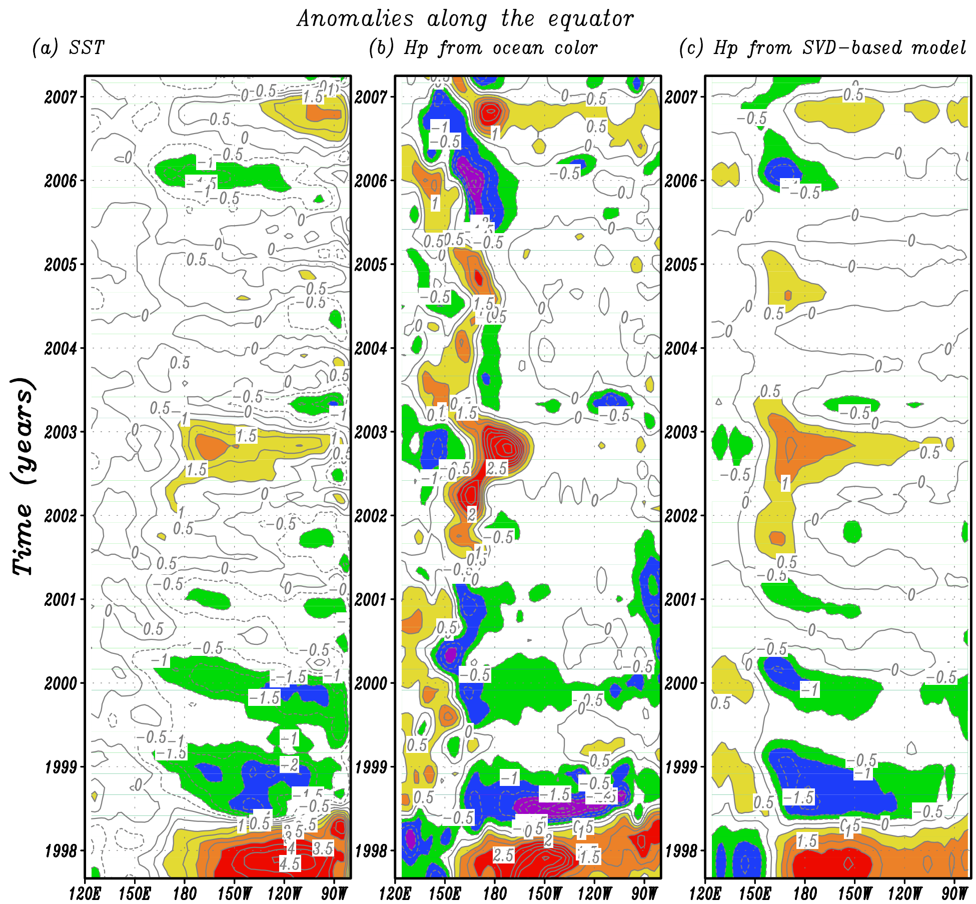

Figure 1. Interannual anomalies along the equator during the period Sep.1997-Apr. 2007: (a) observed SST, (b) H_p derived from the ocean color data, and (c) H_p simulated from SST anomalies using the SVD-based empirical model with the first two modes retained. The contour interval is 0.5 °C in Figure 1a and 0.5 m in Figures 1b and 1c.

coherent co-variability pattern during ENSO cycles. For example, large-scale SST anomalies are generated by ENSO. The response in ocean biology is quick and almost simultaneous, as represented in the H_p fields whose interannual variations follow SSTs closely in the deep tropics. Clearly, both SST and H_p fields are simultaneously responding to the dynamical changes associated with ENSO; the ocean biology induced feedback impacts on SST can provide additional coupled bio-physical interactions which need to be adequately taken into account in modeling. Since SSTs represent the forcing in terms of coupling to the atmosphere, we have a rationale for deriving a feedback model relating interannual H_p variability to SST forcing.

2.2. An Empirical Model for the Attenuation Depth of Solar Radiation

[6] We analyze the SST-H_p relationship on interannual time scales using SVD methods, which allow us to determine their statistically optimized empirical modes from their historical data [e.g., *Zhang et al.*, 2006]. The analysis period is from September 1997 to April 2007 and the analysis domain is confined to the tropical Pacific from 25°S to 25°N and from 124°E to 76°W. The first five SVD modes explain about 54.7%, 10.2%, 7.0%, 3.7%, and 3.3% of the covariance. The spatial structure of the first derived SVD mode illustrates coherent patterns of interannual SST and H_p anomaly fields in the tropical Pacific (figures not shown).

[7] Then, an empirical H_p model can be constructed using the derived spatial patterns of the SVD modes (see *Zhang and Busalacchi* [2009] for a detailed example). Considering the sequence of the singular values and the reconstructions of interannual H_p variability from SST anomalies, only the first two SVD modes are retained (the inclusion of higher modes does not change the results significantly). Figure 1c exhibits one example of the H_p anomalies calculated using the empirical H_p model from the given SST anomalies (Figure 1a). The model captures the large-scale interannual H_p variability during the ENSO evolution. However, as compared with the original field (Figure 1b), the amplitude is systematically underestimated by a factor of about 2. Since some variance is always lost inevitably due to only some limited SVD modes retained in the empirical model, an amplification factor (α_{Hp}) is introduced to rescale its amplitude back to match what is derived from the ocean color data (Figure 1b).

[8] Note that the SST and H_p fields used for computing the SVD modes-based model are varying at the interannual timescale only, and the derived model is for estimating interannual H_p anomalies in the tropical Pacific associated with ENSO. Our previous efforts along these lines specified H_p in an uncoupled manner with physical parameters [e.g., *Murtugudde et al.*, 2002; *Ballabrera-Poy et al.*, 2007]. Here H_p is a physical state-dependent parameter that allows for a feedback from ocean biology to the climate system and their

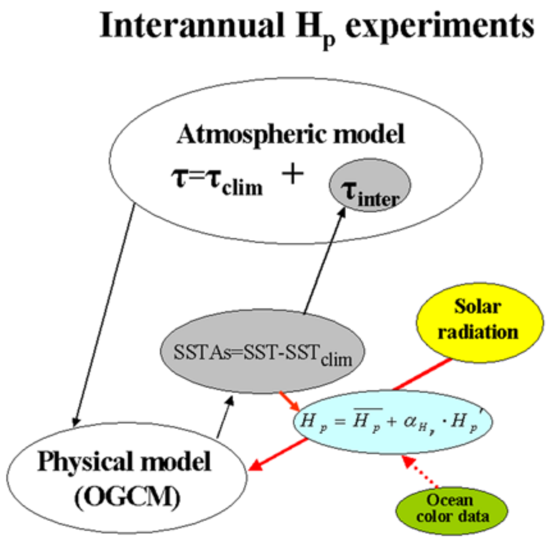

Figure 2. A schematic illustrating a hybrid coupled model (HCM) for the tropical Pacific ocean-atmosphere system, consisting of an OGCM and a simplified atmospheric model, whose forcing fields to the ocean include three components: wind stress, freshwater flux and heat flux (see *Zhang and Busalacchi* [2009] for more details). An empirical model for interannual variability of the penetration depth of solar radiation (H_p), derived from the ocean color data, is also explicitly included to represent the OBF.

active interactions during ENSO cycles, an approach taken by *Timmermann and Jin* [2002] to examine the ocean biology effect on climate.

2.3. Hybrid Coupled Ocean-Atmosphere Model

[9] A hybrid coupled model (HCM) for the tropical Pacific ocean-atmosphere system has been developed at ESSIC [*Zhang et al.*, 2006]. Figure 2 illustrates a schematic for the HCM. Its ocean general circulation model (OGCM) is a primitive equation, sigma coordinate model whose details are given by *Murtugudde et al.* [2002]. The OGCM domain covers the tropical Pacific basin from 25°S to 25°N and from 124°E to 76°W, with the horizontal resolution of 1° in longitude and 0.5° in latitude, and 31 layers in the vertical. The atmospheric wind stress anomaly (τ_{inter}) model is also constructed empirically from the SVD analysis, specifically relating τ_{inter} variability to large-scale SST anomalies ($\mathbf{SST}_{inter}$). The attenuation depth of solar radiation (H_p) in the upper ocean is written as $H_p = \overline{H_p} + \alpha_{Hp} \bullet H'_p$, consisting of the prescribed climatological part ($\overline{H_p}$) and its interannual part (H'_p). The former is prescribed from a long-term annual mean field [*Ballabrera-Poy et al.*, 2007], and the latter is calculated from the $\mathbf{SST}_{inter}$ anomalies. A scalar parameter, α_{Hp}, is introduced to represent the OBF strength. More recently, anomalous freshwater flux forcing has been also included in the HCM to take into account the induced positive feedback in the tropical Pacific climate system [*Zhang and Busalacchi*, 2009].

3. Impacts of the OBF on Interannual Variability

[10] A control HCM run was performed in which interannual H_p variability is not allowed to feedback to SST in the HCM. As shown by *Zhang and Busalacchi* [2009], the model can simulate interannual oscillations well. Next, we perform a series of runs in which the H_p-**SST** relationship derived from satellite data is included to take into account the OBF and interactions between ocean biology and physics (Figure 2), with all the other model settings exactly the same as the control run. Note that the seasonally varying SST climatology ($\mathbf{SST_{clim}}$) fields specified to compute large-scale SST_{inter} anomalies are all the same, which are determined from the forced OGCM climatological simulations.

[11] Varying values of α_{Hp}, representing the OBF strength, are tested to investigate its effect on interannual variability. One example of simulated SST anomaly fields is shown in Figure 3 for two feedback runs with α_{Hp} = 1.0 and α_{Hp} = 3.0, respectively. Simulations with α_{Hp} = 0.0 are analyzed by *Zhang and Busalacchi* [2009], which are almost identical to those with α_{Hp} = 1.0 since interannual H_p variability in the α_{Hp} = 1.0 run is considerably weaker.

[12] A striking feature is that the coupled models depict a pronounced interannual oscillation, with a dominant standing pattern of SST variability on the equator. As is well understood, the positive feedback associated with the wind-SST-thermocline coupling sustains interannual variability in the coupled system. When the OBF is taken into account, the effects can be clearly seen on the amplitude and oscillation periods of interannual variability (Figure 3). The SST anomalies are weaker in the OBF runs, and become even weaker as the OBF is intensified. For example, as represented by the Niño3 SST anomalies (Figure 3c), a significant modulating effect can be seen in years 32 and 45, with the ENSO amplitude having a difference of more than a factor of two. Moreover, runs with the OBF explicitly included exhibit clear phase differences as well. For example, a phase lead starts to show up clearly in year 30 due to an earlier transition from the warm to cold phases in the α_{Hp} = 3.0 run. As such, the inclusion of the OBF causes a clear change in the oscillation periods. This can be more clearly seen in the power spectra estimated from the Niño3 SST indices (figures not shown): the interannual variability has a sharp peak at 4.2 years in the α_{Hp} = 1.0 run, but has shifted toward higher frequency band in the α_{Hp} = 3.0 run, with two enhanced power peaks at 4.2 years and at 3.6 years, respectively. These results indicate that the ocean biology induced feedback effects tend to shorten the persistent time scales of SST anomalies. In addition, the irregularity is evidently large in the no and weak OBF runs (e.g., the years 32 and 45 in Figure 3), but is significantly reduced in the α_{Hp} = 3.0 run due to the damping OBF effects on the system. Also, there is a change in the annual phasing of ENSO events, especially the peak season shifting from winter to summer. Some of these effects are not seen by *Timmermann and Jin* [2002], who used a simpler coupled model and a simpler formulation of the feedback.

[13] The effects are further quantified in Table 1. The standard deviation (std) of Niño3 (Niño4) SST anomalies is 0.76 °C (0.85°C) in the control run (α_{Hp} = 0.0); it is reduced to 0.65°C (0.78°C) in the α_{Hp} = 2.0 run, and to 0.59 °C (0.69°C) in the α_{Hp} = 3 run, respectively. Relative to the control run, these values represent a decrease of the amplitude by 14% (8%) in the α_{Hp} = 2.0 run and by 22% (19%) in the α_{Hp} = 3.0 run. Also, the std of the zonal wind stress in the Niño4 region is 0.19 dyn cm^{-2} in the α_{Hp} = 0.0 run; it decreases to 0.17 dyn cm^{-2} in the α_{Hp} = 2.0 run (a reduction

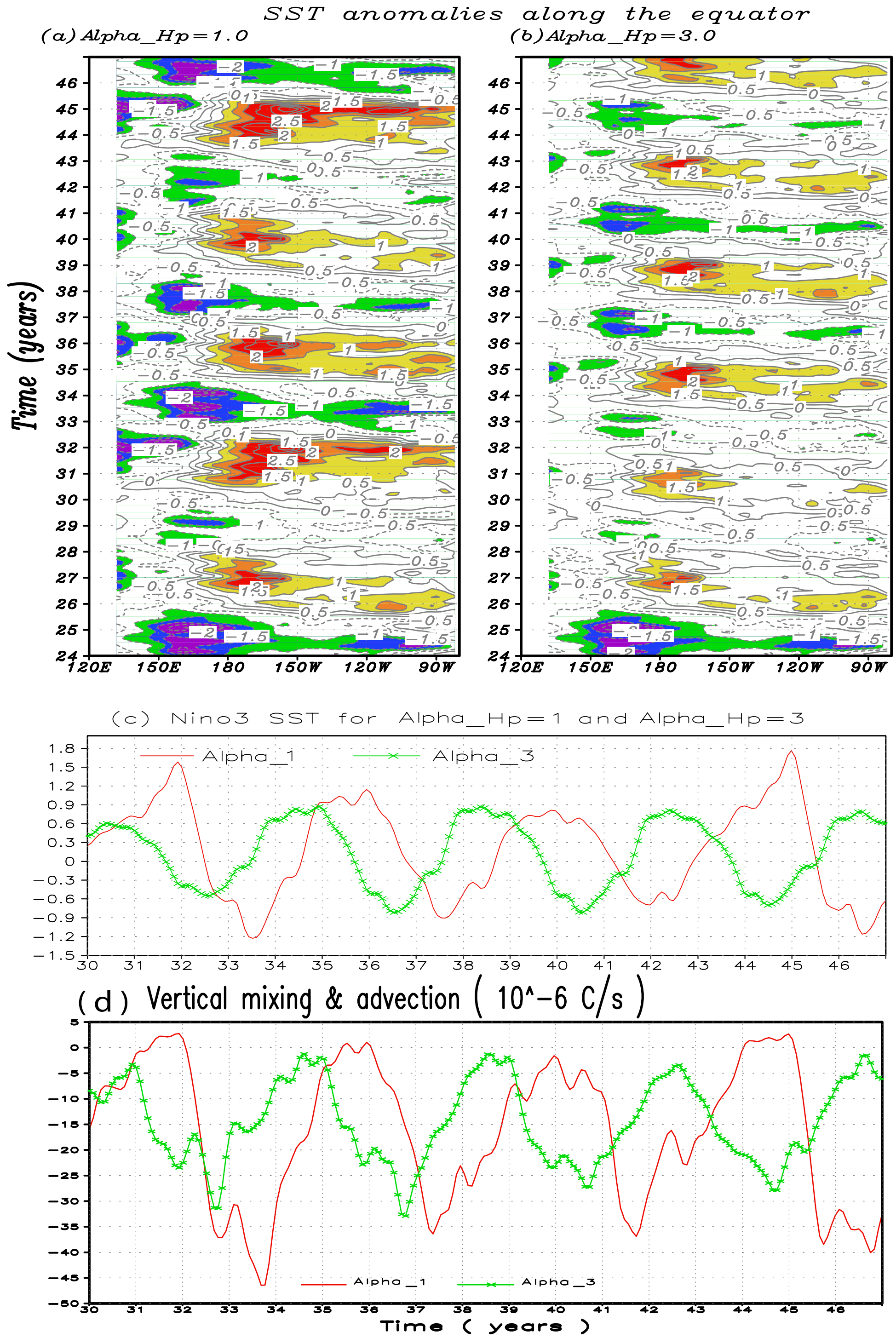

Figure 3. Longitude-time sections of SST anomalies along the equator simulated from the HCM with (a) α_{Hp} = 1.0 and (b) α_{Hp} = 3.0, (c) their time series of Niño 3 SST anomalies, and (d) time series of the sum of vertical mixing and advection terms at 160 °W on the equator. The contour interval is 0.5 °C in Figures 3a and 3b, and the unit is °C s^{-1} $\times 10^{-6}$ in Figure 3d.

by 11%) and to 0.15 dyn cm^{-2} in the α_{Hp} = 3.0 run (a reduction by 21%). Thus, a significant fraction of the SST and surface wind variability can be attributed to the OBF effect in our model simulations.

[14] A heat budget analysis has been preformed to understand processes by which the OBF is affecting interannual variability (Figure 3d). When the OBF is included, the induced feedback acts to reduce the cooling effect of the vertical mixing and entrainment during La Niña (i.e., less cooling), but increase their cooling effect during El Niño (i.e., less warming). This indicates that the inclusion of the OBF effects acts to counteract the positive SST-wind-thermocline feedback, leading to a weakening SST variability during ENSO cycles.

[15] These results can be explained in terms of a negative feedback between ocean biology and climate system as

Table 1. Standard Deviation of Some Selected Anomaly Fields From the HCM Simulations With Varying OBF Strength[a]

	α_{Hp} = 0.0	α_{Hp} = 1.0	α_{Hp} = 2.0	α_{Hp} = 3.0
		Niño4		
SST	0.85	0.85	0.78	0.69
τ_x	0.19	0.19	0.17	0.15
MLD	6.7	6.3	5.4	4.7
SSS	0.16	0.16	0.15	0.13
H_p	0.0	0.47	0.83	1.09
Q_T	8.6	8.5	7.4	3.2
		Niño3		
H_p	0.0	0.27	0.46	0.62
SST	0.76	0.74	0.65	0.59
		Niño12		
SST	0.57	0.56	0.51	0.47

[a]Shown are standard deviations (std) for SST, zonal wind stress (τ_x), MLD, sea surface salinity (SSS), the attenuation depth (H_p), and heat flux (Q_T). As a reference, the std of H_p in the Niño4 and Niño3 regions are 1.14 m and 0.76 m for the ocean color data based calculation (Figure 1b) and 0.63 m and 0.38 m for the empirical model simulation (Figure 1c), respectively. The unit is: °C for SST, dyn cm^{-2} for τ_x, meter for MLD and H_p, W m^{-2} for Q_T, and psu for SSS.

follows. ENSO cycles are characterized by SST anomalies over the equatorial regions, which induce a biological response, as represented by large interannual H_p variability. During La Niña when SSTs are low in the eastern and central tropical Pacific, H_p is negative and the solar radiation attenuates with depth strongly in the vertical. More solar heating is thus trapped in the mixed layer (ML), with less penetration downward into the subsurface. The direct effects are to add the solar heating more in the surface layer but less in the subsurface layers. The induced differential solar heating in the vertical acts to enhance the stratification and thus stabilize the upper ocean, with reduced mixing and entrainment of subsurface waters (e.g., Figure 3d). These oceanic processes tend to weaken the cold SST anomalies generated by La Niña, with the wind-feedbacks favoring further reduction in upwelling and SST cooling. The effects on El Niño can be also seen but with opposite sense. As a result, the inclusion of the OBF in the HCM induces additional oceanic processes that act to counteract the positive SST-wind-thermocline feedback, thus reducing the strength of interannual variability.

[16] Note that in these simulations the OBF effects could be still underestimated in terms of the interannual H_p variability. As estimated from the ocean color data, the standard deviation of the H_p observations is 1.14 m and 0.76 m in the Niño4 and Niño 3 regions. In the SVD analysis, the first two modes contain about 65% of the interannual H_p variance. To compensate for the loss of the covariance, $\alpha_{Hp} = 2$ needs to be taken to recover the strength of interannual H_p variability as observed. In practice, on the other hand, the actual HCM simulation in the α_{Hp} = 2.0 run has the std of 0.83 m and 0.46 m in the Niño 4 and Niño 3 regions (Table 1). Even taking α_{Hp} = 3.0, it is only 1.09 m and 0.62 m. Thus, the simulated interannual H_p variability is still weak in the HCM simulations as compared with that derived from the ocean color data.

4. Concluding Remarks

[17] Recent satellite-based ocean color measurements have shown clear evidence of bio-physical interactions associated with ENSO. Previous studies have identified the role of ocean biology in the modulation of ENSO [e.g., *Timmermann and Jin*, 2002]. In this work, the remotely sensed ocean color data are used to develop an empirical model for interannual H_p variability. The adopted SVD analysis technique allows for a non-local, SST-dependent, and spatially varying representation of the feedback effects and bio-physical coupling around the entire tropical Pacific basin.

[18] The derived H_p model is then incorporated into a basin-scale hybrid coupled ocean-atmosphere model of the tropical Pacific. When the OBF is explicitly incorporated into the HCM, large effects are found on interannual variability, as seen in previous modeling studies [e.g., *Timmermann and Jin*, 2002]. Moreover, some new results emerge in our modeling experiments, including the effects on the irregularity, oscillation periods, and seasonal and interannual phasing of the ENSO. A negative feedback is postulated to explain the weakening effect on interannual variability and the shortening effect on oscillation periods. These results support the view that the ocean biology-induced feedback and bio-physical coupling can be a new contributor to ENSO variability. It is thus necessary to explicitly include the OBF in large-scale climate models. Since the OBF effect is only beginning to be taken into account adequately in some large-scale ocean-atmospheric modeling studies, the empirical H_p model constructed from the ocean color data in this work provides a simple way to parameterize the OBF that can be easily incorporated into any coupled ocean-atmosphere model.

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References

Anderson, W. G., A. Gnanadesikan, R. Hallberg, J. Dunne, and B. L. Samuels (2007), Impact of ocean color on the maintenance of the Pacific Cold Tongue, *Geophys. Res. Lett.*, *34*, L11609, doi:10.1029/2007GL030100.

Ballabrera-Poy, J., R. Murtugudde, R.-H. Zhang, and A. J. Busalacchi (2007), Coupled ocean-atmosphere response to seasonal modulation of ocean color: Impact on interannual climate simulations in the tropical Pacific, *J. Clim.*, *20*, 353–374.

Chavez, F. P., et al. (1999), Biological and chemical response of the equatorial Pacific ocean to the 1997–98 El Niño, *Science*, *286*, 2126–2131.

Lengaigne, M., et al. (2007), Influence of the oceanic biology on the tropical Pacific climate in a coupled general circulation model, *Clim. Dyn.*, *28*, 503–516.

Lewis, M. R., M. E. Carr, G. C. Feldman, W. Esaias, and C. McClain (1990), Influence of penetrating solar radiation on the heat budget of the equatorial Pacific, *Nature*, *347*, 543–546.

Manizza, M., C. Le Quéré, A. J. Watson, and E. T. Buitenhuis (2005), Bio-optical feedbacks among phytoplankton, upper ocean physics and sea-ice in a global model, *Geophys. Res. Lett.*, *32*, L05603, doi:10.1029/2004GL020778.

Marzeion, B., A. Timmermann, R. Murtugudde, and F. F. Jin (2005), Biophysical feedbacks in the tropical Pacific, *J. Clim.*, *18*, 58–70.

McClain, C. R., et al. (1998), Science quality SeaWiFS data for global biosphere research, *Sea Technol.*, *39*, 10–16.

Murtugudde, R., J. Beauchamp, C. R. McClain, M. Lewis, and A. J. Busalacchi (2002), Effects of penetrative radiation on the upper tropical ocean circulation, *J. Clim.*, *15*, 470–486.

Nakamoto, S., S. P. Kumar, J. M. Oberhuber, J. Ishizaka, K. Muneyama, and R. Frouin (2001), Response of the equatorial Pacific to chlorophyll pigment in a mixed layer isopycnal ocean general circulation model, *Geophys. Res. Lett.*, *28*, 2021–2024.

Strutton, P. G., and F. P. Chavez (2004), Biological heating in the equatorial Pacific: Observed variability and potential for real-time calculation, *J. Clim.*, *17*, 1097–1109.

Sweeney, C., et al. (2005), Impacts of shortwave penetration depth on large-scale ocean circulation and heat transport, *J. Phys. Oceanogr.*, *35*, 1103–1119.

Timmermann, A., and F.-F. Jin (2002), Phytoplankton influences on tropical climate, *Geophys. Res. Lett.*, *29*(23), 2104, doi:10.1029/2002GL015434.

Wang, X. J., J. Christian, R. Murtugudde, and A. J. Busalacchi (2005), Ecosystem dynamics and export production in the central and eastern equatorial Pacific: A modeling study of impact of ENSO, *Geophys. Res. Lett.*, *32*, L02608, doi:10.1029/2004GL021538.

Wetzel, P., et al. (2006), Effects of ocean biology on the penetrative radiation in a coupled climate model, *J. Clim.*, *19*, 3973–3987.

Zhang, R.-H., and A. J. Busalacchi (2008), Rectified effects of tropical instability wave (TIW)-induced atmospheric wind feedback in the tropical Pacific, *Geophys. Res. Lett.*, *35*, L05608, doi:10.1029/2007GL033028.

Zhang, R.-H., and A. J. Busalacchi (2009), Freshwater flux (FWF)-induced oceanic feedback in a hybrid coupled model of the tropical Pacific, *J. Clim*, in press.

Zhang, R.-H., A. J. Busalacchi, and R.G. Murtugudde (2006), Improving SST anomaly simulations in a layer ocean model with an embedded entrainment temperature submodel, *J. Clim.*, *19*, 4638–4663.

Zhang, R.-H., A. J. Busalacchi, and D. G. DeWitt (2008), The roles of atmospheric stochastic forcing (*SF*) and oceanic entrainment temperature (T_e) in decadal modulation of ENSO, *J. Clim.*, *21*, 674–704.

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